Lunar Traverse Missions

R. G. Brereton and J. D. Burke

Advanced Technical Studies Office

R. B. Coryell

Project Engineering Division

L. D. Jaffe

Space Sciences Division

The results of recent JPL studies on Lunar Traverse Missions are compared with the announced characteristics of the Soviet Lunokhod 1 rover, delivered to the Moon by the *Luna 17* spacecraft in November 1970. Except for some differences in emphasis among the scientific experiments, the Lunokhod mission is quite similar to those recommended in the JPL studies.

Introduction

It has long been recognized (References 1–3) that mobility is essential for exploring lunar and planetary surfaces. For the past several years, scientists and engineers at JPL have been working on various aspects (References 4–15) of lunar and planetary roving missions to prepare for the time when it would be possible to carry instrument payloads on mobile vehicles controlled from Earth. When the Soviet spacecraft *Luna 17* delivered an automated rover, Lunokhod 1 (Figures 1, 2, and 3), to the Moon, this prospect became a reality. In this article, we compare the results of our studies with the announced data (References 16 and 17) on the Lunokhod mission, whose main objectives appear to be almost exactly those recommended for an early mission by the JPL study teams.

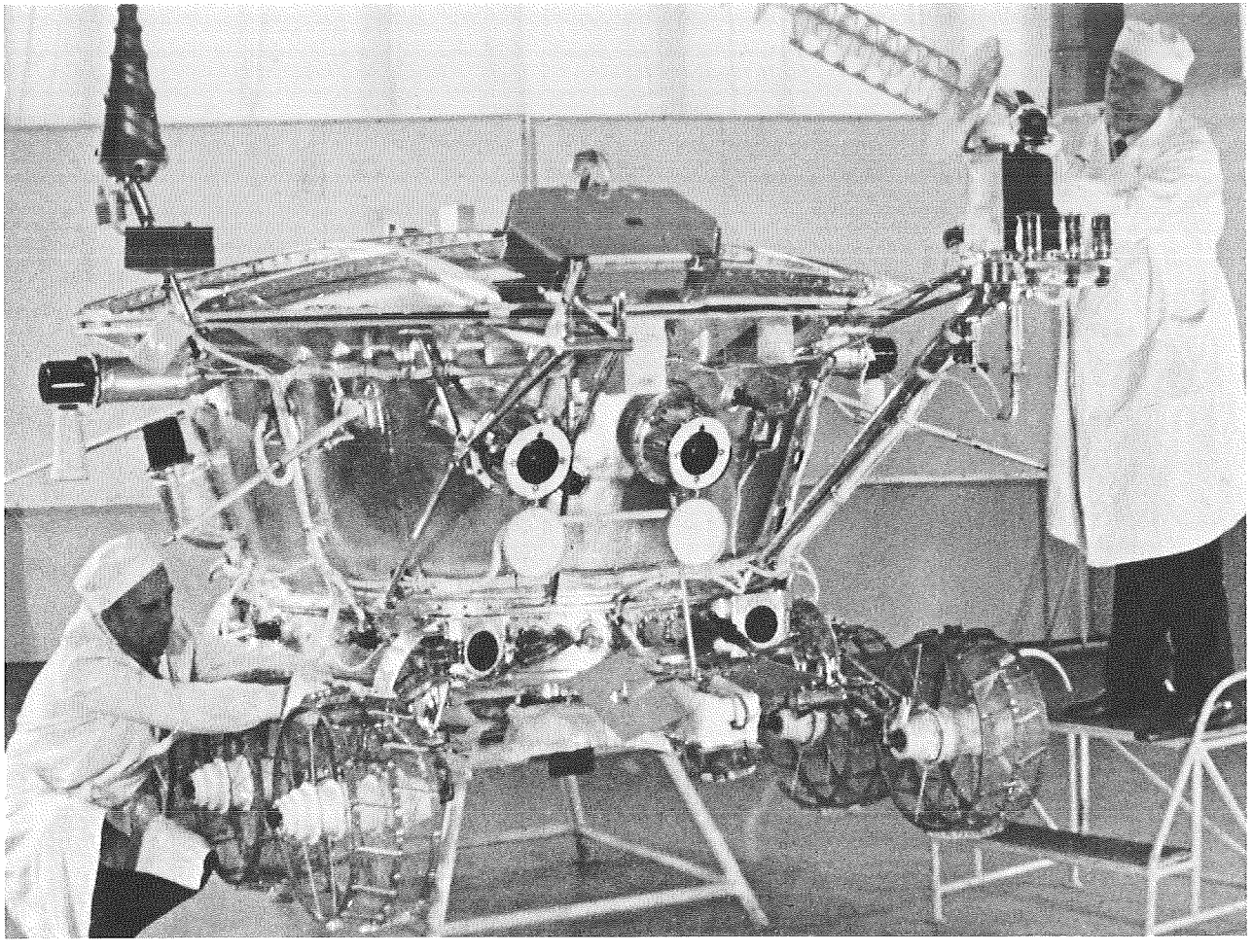

Figure 1. Soviet Moon Car Lunokhod 1 in testing-assembling building prior to flight of *Luna 17*. Two TV cameras are at front; dark cylindrical objects at sides are telephotometer (facsimile) cameras, two scanning in vertical plane and two scanning slightly below horizontal (photo credit: TASS from SOVFOTO)

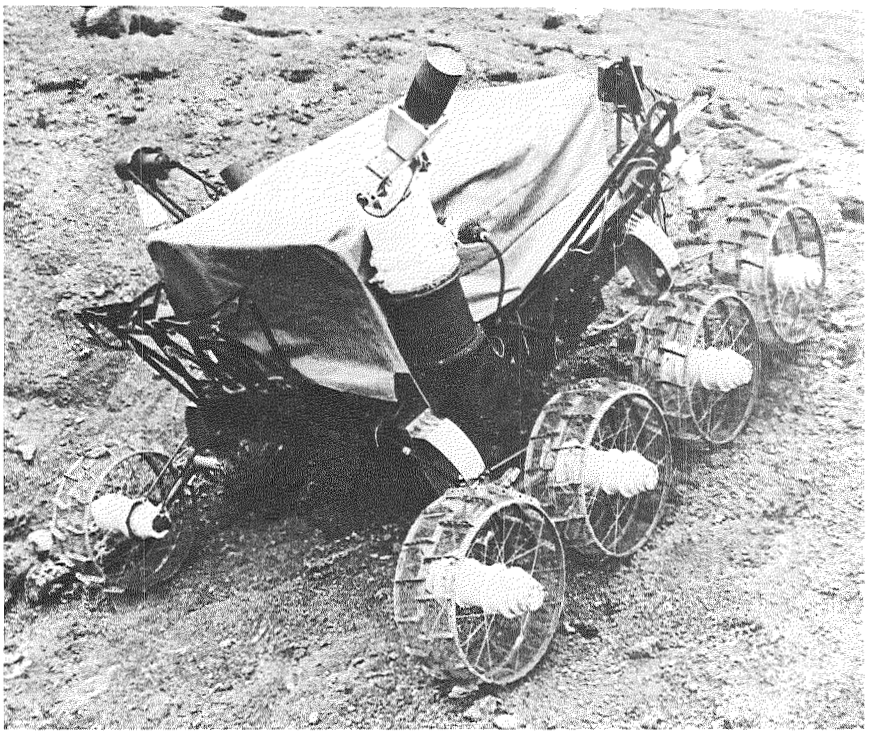

Figure 2. Working parts of Lunokhod 1 pictured during test at Lunodrome (photo credit: TASS from SOVFOTO)

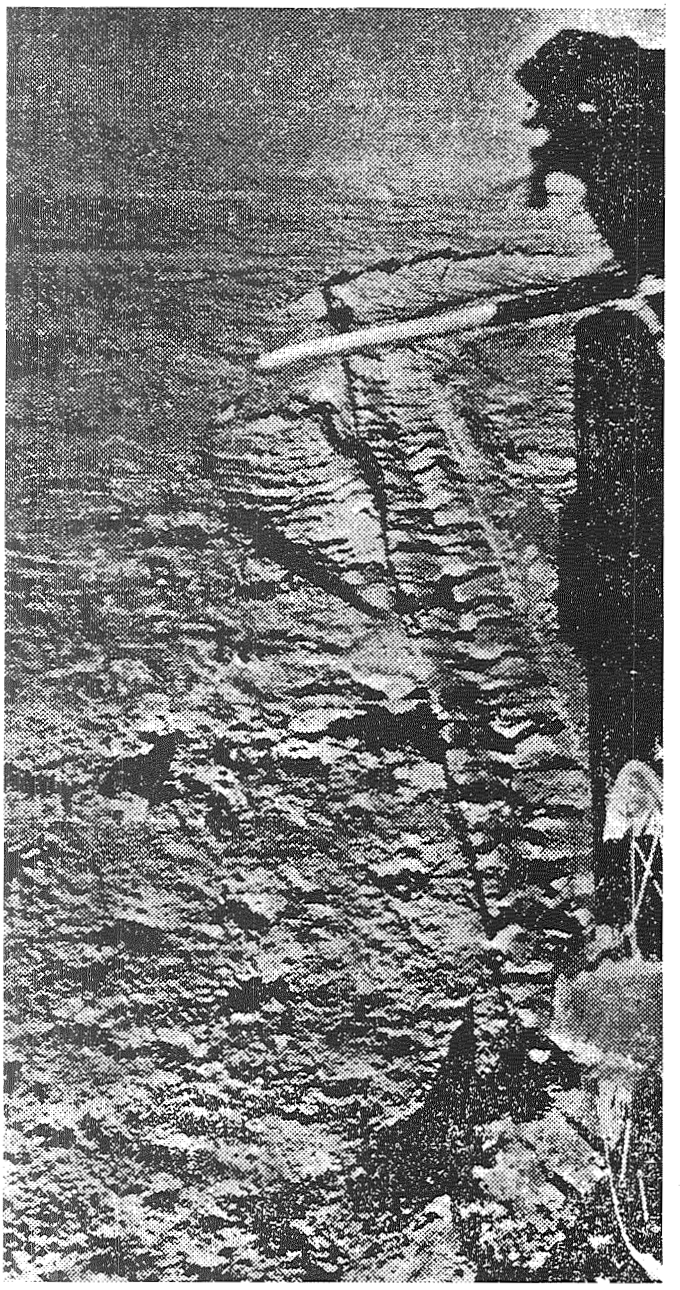

Figure 3. Image of lunar surface from Lunokhod telephotometer (facsimile) camera showing one wheel and tracks left by vehicle (photo from Pravda)

Lunar Scientific Objectives

The major goal of lunar scientific exploration remains to determine the origin and history of the Moon and its implications for the origin and history of the Earth and the solar system. In the JPL studies, the following major questions, whose answers would meet this goal, were posed:

(1) Initial source of bulk lunar material:

  (a) Where was its location in the circumsolar cloud?

  (b) What was its pre-accretion chemical evolution?

(2) Mode of accumulation of the Moon:

  (a) Did it accumulate by independent accretion or by derivation from the Earth?

  (b) What was the time of accumulation, i.e., the elapsed time since the effective cessation of nucleosynthesis?

  (c) What was the duration of accumulation?

(3) Post-accretion lunar history:

  (a) What are the major Moon-wide geological processes and their energy sources?

  (b) What is their chronology?

The following prerequisite investigations, whose results would provide a basis for answering the major questions, were suggested:

(1) The distribution of surface chemical and isotopic compositions, including trace elements.

(2) The internal structure and petrology and the physical state of the interior.

(3) The present thermal regime including internal temperature distribution, surface heat flow, and abundances and distribution of heat sources.

(4) The correlation among morphology, composition, and chronology of surface material.

At post-*Apollo* time, it is unlikely that satisfactory answers to these questions will have been obtained. Automated rovers will not provide direct answers to the major questions and prerequisite investigations, but they can provide a unique means for step-by-step accumulation of essential data.

Essential Rover Measurements

The optimum geological measurements for rovers are those that characterize surface geological units in terms of morphology and composition and those of a geophysical nature that permit determination of deeper subsurface structure. Desirable parameters for measurement are those that are likely to vary over a long traverse in a way that can be correlated with lithology or morphology as deduced from *Apollo* and *Lunar Orbiter* photographs. Undesirable parameters are those that are likely to vary randomly over the whole surface or with time.

Based on the above criteria, a few relatively simple, fundamental surface measurements are essential for a traverse over previously unexplored lunar regions. These measurements are practical and likely to be most feasible within the expected constraints of a rover program.

(1) *Imaging.* There should be:

(a) Continuous high-resolution imaging in the visible spectrum, ideally in color and with spatial resolution of at least 0.1 mm in close-up mode.

(b) Monoscopic and stereoscopic panoramic views, and magnified views of selected outcrops as well as of individual rock fragments.

(c) Search for bedrock, and delineation of field relations of rock units; e.g., distinction of intrusive and depositional contacts. It is important that the undisturbed regolith surface be viewed *in situ* and close up, since return of undisturbed surface material to Earth is difficult.

(2) *Characterization of surface material.* The bulk elemental composition of surface materials must be found using some easily measured parameters. Gamma-ray spectrometry and spectral reflectance are possible techniques.

(3) *Elemental and mineralogical characterizations.* Detailed elemental and mineralogical characterization via neutron activation and X-ray diffraction methods can be made on selected specimens at sites of special interest (Reference 18).

(4) *Geophysical measurements* should be made as follows:

(a) Gravity profiles (discrete measurements with spacing depending on observed variations).

(b) Heat flow measurements with sensitivity sufficient for detecting fluxes of 4.184×10^{-6} J-s^{-1}-cm^{-2} (10^{-6} cal-s^{-1}-cm^{-2}).[1] This is a difficult measurement and may not be feasible for an automated rover.

(c) Seismic measurements using deployed surface charges as well as natural events.

Instrumentation Techniques

Imaging

The essential instrument for guiding and navigating a rover and for observing and sampling the lunar surface to achieve the above objectives is an imaging system. The technical requirements on image quality and telecommunications bandwidth are such that two types of cameras are needed; the total number of cameras may be more than two, for redundancy or for convenience in achieving desired fields of view. The two types of cameras and their functions are listed in Table 1.

Table 1. Rover imaging systems

JPL imaging sensor requirement	Function	Lunokhod design
Television		
Near field ahead and to sides	Guidance (driving) and sampling	Two forward-looking TV cameras, one wide-angle, one narrow-angle
Close-up with magnification	Sample investigation	
Far field	Magnified views of distant features	
Photofacsimile		
Horizon panorama	Landmark navigation and geologic reconnaissance	Four telephotometers, two scanning horizon, two scanning fore and aft through vertical
Near field	Geologic observation and redundancy with TV	

On the basis of *Surveyor* and *Apollo* observations, a survey of opinions among scientists, and laboratory tests, some conclusions of the JPL imaging studies were:

(1) Stereo is desirable but not essential in the near field for driving.

[1]Where applicable, the International System of Units is stated first, followed by the customary units in parentheses. In each case, the value in parentheses represents the measured or calculated unit.

(2) Magnification and manipulation, i.e., changing illumination and viewing angles, are essential for the close-up petrologic analysis of samples, and a large depth-of-field is highly desirable.

(3) Color is not needed for the panoramic or near-field lunar views, but is highly desirable in the magnified close-ups.

The Lunokhod system apparently does not include color and is not optimized for stereo, and sample collection and manipulation are not provided. However, the system does have the main characteristic recommended; namely, it uses television for the near-field and driving functions (where speed of display is more important than picture quality) and photofacsimile for panoramic reconnaissance (where high resolution and high photometric, dimensional, and spectral fidelity are desired), with some overlap for redundancy.

Orientation and Navigation

On the basis of studies, laboratory experiments, and field tests (Reference 7) in the California desert (Figures 4 and 5), the JPL teams devised a practical scheme for landmark navigation and evaluated the requirements for rover imaging and other sensors as well as ground displays and command functions. Table 2 summarizes these results.

Table 2. Rover navigation

JPL requirement	Function	Lunokhod design
Horizon landmark identification and bearings	Position fix	Telephotometers, i.e., photofacsimile cameras
Sun, Earth azimuth and elevation	Orientation, rough position	Telephotometers and antenna servo positions
Vehicle pitch, roll and heading relative to local vertical	Orientation and hazard limit sensing	Tilt sensors in telephotometer field of view, and sun or shadow azimuth
Distance travelled	Dead reckoning	Odometer on extra towed wheel, sensors on driving wheels
Direction travelled	Dead reckoning	Unknown

It is not obvious from announcements made to date that the Lunokhod uses or needs a landmark navigation system, since it moved only a few kilometers and then returned to its landing point. It does have all the other functions listed in Table 2. The JPL studies (Reference 19) showed that landmark navigation is the only practical way to attain the accuracy needed on a traverse of hundreds of kilometers. Competing techniques such as inertial or celestial navigation require more instrumentation and

Figure 4. Lunar navigation and geological sampling field simulation test. Operators inside sealed van view terrain and samples via TV

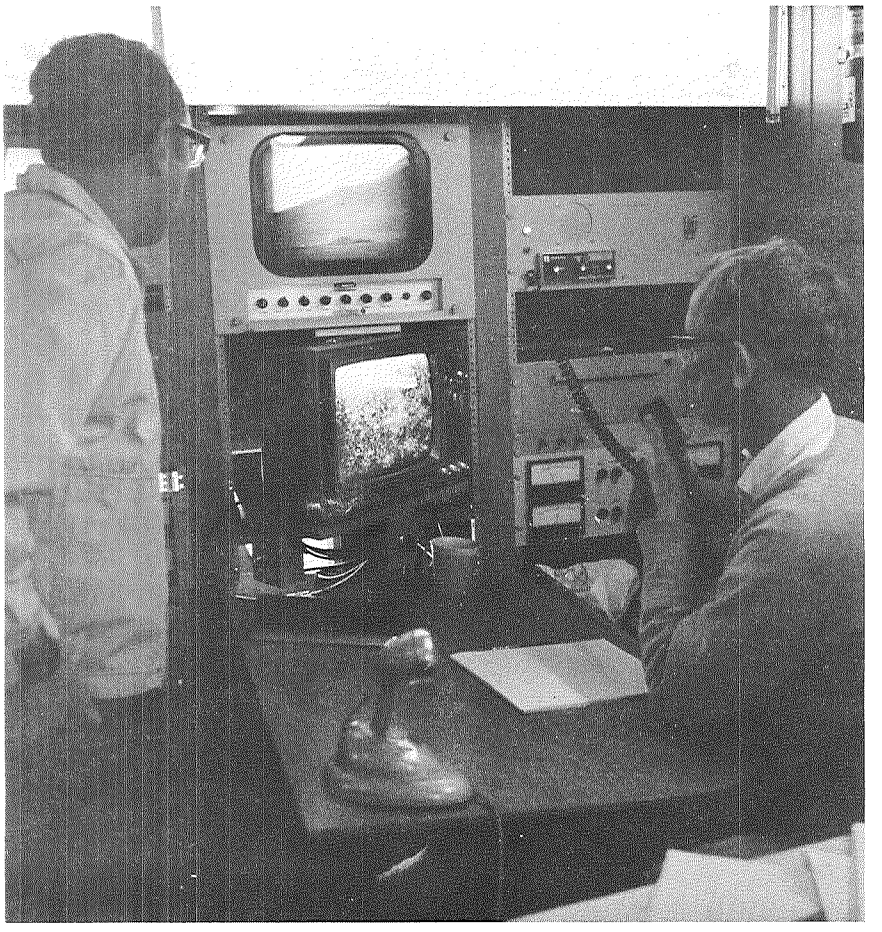

Figure 5. Interior of van (simulating Earth-based control center) showing pictorial displays: (top) panorama, (center) magnified view of part of horizon, (bottom) close-up of samples

do not offer comparable performance for the particular missions considered feasible early in a surface exploration program. Of course, the use of landmarks is limited to areas previously mapped, for example, by lunar orbiters; this is not a severe constraint for the missions studied.

Other Scientific Instruments

In addition to the television and facsimile instruments and sample manipulation device, it was concluded (as mentioned above and in References 5, 7, and 8) that early lunar rovers should carry limited instrumentation for measuring surface chemical composition, e.g., an X-ray diffractometer/spectrometer, and also, if possible, geophysical instruments such as a gravimeter and precision ranging transponder.

The Lunokhod payload includes an X-ray spectrometer that can be deployed to the lunar surface to measure soil composition, a pene-

trometer-and-vane device for measuring soil bearing and shear strength, and radiation detectors for determining the lunar radiation background environment. In addition, the rover carries an X-ray telescope aimed near the zenith with sensitivity in the 2×10^{-10} to 10×10^{-10}-m (2 to 10-Å) region and about a 52-mrad (3-deg) field of view, and a French-built laser retroreflector.

The Soviet spacecraft therefore is attempting experiments closely similar to those recommended for U.S. automated rovers for initial reconnaissance, but with relatively less emphasis on lunar mineral sampling and internal properties, and relatively more emphasis on radiation and astronomical measurements. Though the precision ranging experiment was recognized in the JPL studies as very important in the study of Earth–Moon motions, it was not recommended that the rover carry a laser reflector, since this appeared more suitable as a fixed-site experiment. The Lunokhod retroreflector, used intermittently now while the rover is stopped at night, can presumably continue in use after the machine finally stops moving.

The Lunokhod design appears adequate for every critical function, with the exception that the long traverse mission requires an order of magnitude higher average speed than Lunokhod 1 has demonstrated. The interaction among rover power supply and demand, lunar lighting, time needed for experiments, safe driving speeds, and ground-system duty cycle was worked out in the JPL studies. The resulting conclusion was that night survival, as now achieved by Lunokhod 1, would be essential because at best only a few tens of kilometers could be covered during each lunar day. The slow progress of Lunokhod 1 may be in part due to power-system limitations, but also probably reflects a proper degree of caution at the start of this new class of missions on the Moon.

References

1. *Exploration of the Moon, the Planets, and Interplanetary Space*, Report 30-1. Edited by A. R. Hibbs. Jet Propulsion Laboratory, Pasadena, Calif., Apr. 30, 1959.

2. *Lunar Exploration-Strategy for Research 1969-1975*, National Academy of Sciences, Space Science Board, Washington, D. C., Sept. 1969.

3. *1967 Summer Study of Lunar Science and Exploration, Santa Cruz, Calif.*, NASA SP-157. Edited by W. N. Hess. National Aeronautics and Space Administration, Washington, 1967.

4. Adams, J. B., et al., "Strategy for Scientific Exploration of the Terrestrial Planets," *Reviews of Geophysics*, Vol. I, pp. 623–661, Aug. 1969.

References (contd)

5. Brereton, R. G., "The Objectives for Roving Vehicles in a Lunar Exploration Program," in *Supporting Research and Advanced Development*, Space Programs Summary 37-52, Vol. III, pp. 253–255. Jet Propulsion Laboratory, Pasadena, Calif., Aug. 31, 1968.

6. Brereton, R. G., "Lunar Mission Planning," in *Supporting Research and Advanced Development*, Space Programs Summary 37-54, Vol. III, pp. 230–238. Jet Propulsion Laboratory, Pasadena, Calif., Dec. 31, 1968.

7. Brereton, R. G., and Howard, E. A., "Comments on Geological Observations From an Automated Vehicle (Field Test)," in *Supporting Research and Advanced Development*, Space Programs Summary 37-55, Vol. III, pp. 258–263. Jet Propulsion Laboratory, Pasadena, Calif., Feb. 28, 1969.

8. Brereton, R. G., "An Active Seismic Experiment for an Automated Roving Vehicle," in *Supporting Research and Advanced Development*, Space Programs Summary 37-56, Vol. III, pp. 213–216. Jet Propulsion Laboratory, Pasadena, Calif., Apr. 30, 1969.

9. Brereton, R. G., "Lunar Surface Gravity Investigations," in *Supporting Research and Advanced Development*, Space Programs Summary 37-57, Vol. III, pp. 1–6. Jet Propulsion Laboratory, Pasadena, Calif., June 30, 1969.

10. Brereton, R. G., Ulrich, G. E., and Dahlem, D. H., "Imaging and Sampling Requirements for an Automated Lunar Roving Vehicle," in *Supporting Research and Advanced Development*, Space Programs Summary 37-60, Vol. III, pp. 1–3. Jet Propulsion Laboratory, Pasadena, Calif., Dec. 31, 1969.

11. Brereton, R. G., "Geophysical Experiments for the Manned Portion of a Lunar Roving Vehicle Mission," in *Supporting Research and Advanced Development*, Space Programs Summary 37-61, Vol. III, pp. 1–4. Jet Propulsion Laboratory, Pasadena, Calif., Feb. 28, 1970.

12. Brereton, R. G., et al., "A Miniaturized Absolute Gravimeter for Terrestrial, Lunar, and Planetary Research," in *Supporting Research and Advanced Development*, Space Programs Summary 37-62, Vol. III, pp. 1–5. Jet Propulsion Laboratory, Pasadena, Calif., Apr. 30, 1970.

13. Brereton, R. G., "Automated Post-Missions for the Lunar Roving Vehicle," in *Supporting Research and Advanced Development*, Space Programs Summary 37-62, Vol. III, pp. 5–8. Jet Propulsion Laboratory, Pasadena, Calif., Apr. 30, 1970.

References (contd)

14. Strand, J. N., "Tests of Instruments Proposed for the Scientific Payload of a Lunar Rover," in *Supporting Research and Advanced Development*, Space Programs Summary 37-62, Vol. III, pp. 15–18. Jet Propulsion Laboratory, Pasadena, Calif., Apr. 30, 1970.

15. Brereton, R. G., "Mission Objectives for a Lunar Roving Vehicle," in *Supporting Research and Advanced Development*, Space Programs Summary 37-64, Vol. III, pp. 1–3. Jet Propulsion Laboratory, Pasadena, Calif., Aug. 31, 1970.

16. *Soviet-Bloc Research in Geophysics, Astronomy, and Space*, JPRS 51991, No. 242. Joint Publications Research Service, Dec. 15, 1970.

17. *Soviet-Bloc Research in Geophysics, Astronomy, and Space*, JPRS 52087, No. 243. Joint Publications Research Service, Dec. 30, 1970.

18. Nash, D. B., *Sampling of Planetary Surface Solids for Unmanned In Situ Geological and Biological Analysis: Strategy, Principles, and Instrument Requirements*, Technical Report 32-1225. Jet Propulsion Laboratory, Pasadena, Calif., Nov. 15, 1967.

19. Lewis, R. A., "A Computerized Landmark Navigator: Development and Test Plan," in *Supporting Research and Advanced Development*, Space Programs Summary 37-65, Vol. III, pp. 1–2. Jet Propulsion Laboratory, Pasadena, Calif., Oct. 31, 1970.